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Climate benefits from alternative energy uses of biomass plantations in Uganda

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ABSTRACT

The establishment of tree plantations in rural areas in Uganda could provide renewable energy to rural communities, while decreasing greenhouse gas emissions from conventional electricity sources and unsustainable forest use. The study evaluates the greenhouse gas benefits that could be produced by biomass based energy systems in Anaka, a rural settlement in the Amuru district in northern Uganda. Two alternative energy uses are explored: a) electricity production through wood gasification and b) traditional fuelwood use. It is estimated that a small-scale wood gasifier could provide electricity for basic community services by planting less than 10 ha of new short rotation coppices (SRCs). The gasification system could save 50–67% of the GHG emissions produced by traditional diesel based electricity generators in terms of CO_2-eq. (0.61–0.83 t MWh^{-1} or 7.1 t y^{-1} per hectare of SRCs). It was also estimated that traditional use of fuelwood in households is currently unsustainable, i.e. the consumption of wood is higher than the annual growth from natural wood resources in the study area. It is estimated that 0.02–0.06 ha per capita of plantations could render the current consumption of wood sustainable. In this way, the CO_2 emissions produced through unsustainable extraction of wood could be avoided (2.0–7.3 t per capita per year or 50–130 t y^{-1} per hectare of SRCs).

1. Introduction

Biomass is the main source of energy in Uganda. National statistics report that 91.5% of energy consumption is derived from the combustion of biomass sources such as fuelwood, charcoal and residues. A very limited share of energy use is covered by electricity (1.1%) and the remaining 7.4% is produced by fossil fuels [1].

Wood biomass will likely remain the dominant household energy source for cooking and heating for several decades in Uganda due to low accessibility to alternative energy sources [2]. In addition, biomass is seen as an option to provide electricity to rural areas where only 1% of the population has access to the grid. High electricity prices, frequent power outages, and high line losses pose hurdles to increasing access to the grid over the short to medium term.

At the same time, forest statistics report that wood resources in Uganda are constantly decreasing [3]. Consequently, biomass based electricity generation or traditional energy from fuelwood can be expected to be constrained by a decreasing availability of wood from forests and other wooded lands. By contributing to the degradation of natural wood resources, biomass based energy

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also contributes to increase greenhouse gas (GHG) emissions in the atmosphere and to climate change.

The establishment of new plantations in developing countries could guarantee wood availability for the future, supply feedstock to renewable energy systems that are accessible to rural communities and produce GHG benefits as compared to fossil fuel based systems and unsustainable wood extraction.

This study assesses the climate mitigation benefits produced by alternative uses of wood plantations, when new Short Rotation Coppices (SRCs) are established on non-forested, low carbon stock land in Uganda. The comparison of GHG benefits from alternative uses of a certain bioenergy source is important to support the most efficient strategies to achieve GHG emission reductions [4,5]. To the knowledge of the authors, this is the first attempt to make such an assessment from wood plantations in Uganda.

Two alternative energy uses of wood plantations in a rural area in Uganda are considered:

a) Electricity from wood gasification; and
b) Firewood for traditional use in households.

The climate mitigation benefits of wood gasification are assessed by applying a GHG balance based on a Life Cycle Assessment methodology. The balance compares the GHG impacts of the gasifier to the impacts of a typical fossil fuel based electricity generation.

In parallel, we assessed the area of SRC plantations needed to supply fuelwood to the rural community. The plantations would avoid degradation of natural biomass resources and thus avoid increasing GHG in the atmosphere. An estimate of the avoided emissions is provided.

2. Methods

2.1. Study area

The study area is located in the Amuru district in the Northern part of Uganda (02°36′0″N, 31°57′0″E). The CLIMWAT database [6] reports an annual precipitation of about 1500 mm y^{-1} and an average annual temperature of 23 °C for the meteorological station in Gulu. Climatic measurements taken in 2005–2007 in Aswa-Lolim, Amuru suggest that the average rainfall could be lower in certain areas of the Amuru district, around 900 to 1000 mm per annum [7].

The Anaka refugee camp in Amuru is the settlement chosen for the installation of the gasifier and the assessment of the impacts of traditional use of fuelwood. The Anaka internally displaced people camp (IDP camp) hosts about 22,450 people. Main electricity users in the camp are the hospital and shops. Anaka is located in the north-western part of a water catchment in which the main land uses are grasslands (727 km^2), followed by agricultural land (214 km^2) and forests (192 km^2) [8]. Currently, grasslands are used for hunting. Most likely, in the near future land will return to small holder agriculture and cattle ranching, as they were before the civil war.

2.2. Biomass for electricity

Previous investigations showed that small-scale wood gasifiers could be an economically and socially feasible energy system to produce electricity in rural Uganda [9]. This study integrates previous analysis by assessing the mitigation potential of wood gasifiers in Uganda. The GHG benefits of electricity generation by wood gasification as compared to electricity originating from diesel generators in the IDP camp of Anaka are evaluated through a GHG balance based on a Life Cycle Assessment methodology.

2.2.1. GHG balance

A GHG balance, based on a Life Cycle Assessment (LCA) methodology, includes all processes, which influence GHG emissions from *cradle to grave* [10]. The GHGs included in the study are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Global Warming Potentials (GWP) on a 100 year time horizon are used to express the contribution of CO_2, CH_4 and N_2O to global warming in terms of equivalent amount of CO_2 (CO_2-eq.) [11].

The GHG balance is performed with the Global Emission Model of Integrated Systems (GEMIS), version 4.5 [12] and project specific data are added to the GEMIS standard data set version 4.5. Two different systems for electricity production are analysed:

- "Electricity wood gasifier – E-WG": Production of electricity with a centralized wood gasification system. The biomass used is supplied from Short Rotation Coppices (SRCs) of *Eucalyptus grandis* Hill ex Maiden.
- "Electricity diesel generator – E-DG": Production of the electricity with decentralized diesel generators.

The GHG balance is based on process chains which are designed for each investigated system: the wood gasification and the reference fossil fuel system (diesel generator). A process chain describes the complete life cycle, starting with the production of raw materials and ending with the supply of energy to the end user (Fig. 1). Emissions or removals from the conversion of grassland to SRCs are also included.

2.2.2. Input data

The electricity demand for the Anaka camp is estimated based on a study conducted in the refugee camp of Kyangwali, Uganda within the project BIOSYRCA [13]. Electricity is used by the hospital and the trading centre of the Anaka camp. In Kyangwali, the electricity demand is estimated to be 25.5 MWh y^{-1}. In this study, a demand of 30 MWh y^{-1} is assumed as a conservative estimate to include a possible increase of demand in the near future and higher electricity needs for the hospital.

The data on the electricity generators are reported in Table 1. The gasifier powers a modified diesel engine that runs on a dual fuel mode. The fuel gas provides 75% of the primary energy input. Diesel is required for start-up operations and to support the systems. A small power grid must be constructed to supply electricity from the gasifier to the main buildings of the refugee camp. The length of transmission lines is assumed to be 2 km to connect the hospital and shops of the trading centre. In the case of diesel generators each of the buildings

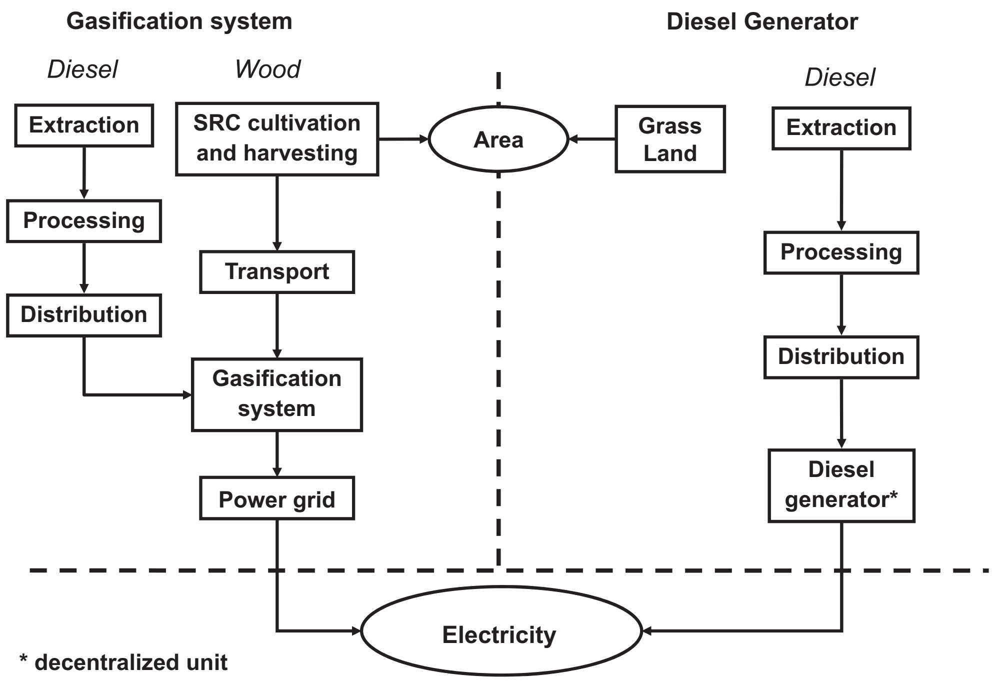

Fig. 1 – Process chains for the centralized wood gasification system and the fossil reference system with decentralized diesel generators.

that require electricity is equipped with a separate diesel generator.

The wood for gasification is supplied by Short Rotation Coppices (SRCs) of *E. grandis*. It is assumed that the plantation density is 2.5 × 2.5 m or equal to a stem density of 1600 ha^{-1}, the maximum rotation length is 6 years [15] and that the annual productivity of the stands ranges between 5 and 15 t ha^{-1} y^{-1} on an oven dry basis [13]. It is also assumed that the productivity of the plantations corresponds to the biomass that can be harvested.

The total planted area needed for the SRCs is calculated based on the productivity of the plantations and the total amount of wood required by the gasification system. The lower heating value of wood is assumed equal to 18 GJ t^{-1} and the electrical conversion efficiency 15% [13]. It is calculated that a wood supply of 30 t y^{-1} is needed to produce an electricity output of 30 MWh y^{-1} from the gasifier, if wood contributes to 75% of the energy input of the dual-mode system. By assuming an annual productivity of 5–15 t ha^{-1} y^{-1}, the final harvest produces 30–90 t ha^{-1}. Therefore the annual demand is met by harvesting 1.0 to 0.33 ha each year. To guarantee a constant annual supply of wood, a total area of 2.0–6.0 ha needs to be converted to Eucalyptus plantations and 1/6 of it is cut every year.

Plantations should be established on areas not used for agricultural production in order to exclude competition with other major land uses, primarily food production. Therefore, the SRCs are planted on an area currently covered by grasslands.

The annual emissions from planting and harvesting are calculated as an average over 20 years, taking into account that harvesting starts in year six and that the plantations are renewed every three rotation periods. The transport emissions are assessed by assuming a maximum distance of 30 km between the plantations and the gasifier. The emissions caused by transportation for planting and harvesting are calculated based on a daily productivity of a team of 3–6 workers. It is assumed that each worker plants 220 seedlings per day and harvests 120 trees per day. The fuel consumption of the truck is assumed to be at 0.165 dm^3 km^{-1}, i.e. 9.9 dm^3 d^{-1}. The harvesting is done with chainsaws. A fuel consumption of 12.8 dm^3 and an oil consumption of 2.9 dm^3 per working day are assumed. The

Table 1 – Basic data on the power generation systems.

Technology	Efficiency (%)	Life span (y)	Operation hours (h y^{-1})	Capacity (kW)	Steel (kg)	Concrete (kg)
Wood gasifier[a] (Bioenergy system)	15	15	3.257	9	500	200
Diesel generator[b] (Reference system)	28	10	3.257	3	100	–

a Type Ankur Gasifier WBG-15/GAS-9; data according to [14] and expert judgement.
b Decentralized units in the main buildings type PRAMAC P4500-PF322SYA; data according to product specification (www.pramac.com).

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emissions caused by use of herbicide and fertilizer before planting are also included. It is assumed that a manual chipping system is used to chip the wood used for the gasifier. Motor driven chippers are very effective, but they require a substantial initial investment, besides constant service and maintenance. Hand operated or spring activated scissors or axes were considered a more suitable option in rural Uganda.

An inventory table of the inputs and outputs of the gasification system is reported in the Appendix.

2.2.3. *Land use change emissions and removals*

The carbon (C) stock changes due to the conversion of grasslands to Eucalyptus plantations are included in the GHG balance. The change is calculated as the difference between the carbon stock of the Eucalyptus plantations and the carbon stock of grasslands on hectare basis. The annual change over a conversion period of 20 years is considered [11]:

$$\Delta C = \frac{(C_E - C_R)}{20} \quad (1)$$

where ΔC: carbon stock change due to land use change (t ha^{-1} y^{-1}), C_E: carbon stock in Eucalyptus SRCs (t ha^{-1}), C_R: carbon stock in grasslands (t ha^{-1}).

Only the carbon stock changes in the biomass are included in the calculation. The conversion of cropland or grassland to plantations will likely increase or maintain unaltered the amount of carbon in soils [16]. Therefore, it is conservatively assumed that the carbon stock changes in the soil are equal to zero [11]. The biomass carbon content of grasslands is derived from IPCC default values (8 t ha^{-1} of C). The biomass in the SRCs is assessed based on a stand productivity of 5–15 t ha^{-1} and an IPCC default root-to-shoot ratio of 0.24 to convert aboveground biomass to root biomass. A carbon fraction in the biomass of 0.47 is assumed [11]. It was assessed that the new SRCs accumulate 9.3–27.8 t ha^{-1} of C after 20 years when belowground biomass is included and when the carbon loss from conversion is not taken into account (8 t ha^{-1} of C). Therefore, the conversion produces a net C sequestration in living biomass of 0.06–1.0 t ha^{-1} y^{-1} or a sequestration of 0.4–2.0 t y^{-1} over the entire area.

2.3. *Biomass for traditional use*

Most rural households in Uganda strongly depend on fuelwood and the collection of wood for traditional use (mainly cooking) significantly contributes to deforestation and forest degradation in Uganda [8,17]. Additional plantations may be used to cover a share of this traditional demand for wood. Using the Anaka IDP camp and the district of Gulu as examples, we assess the area of additional plantations needed to supply sufficient wood for traditional use without causing deforestation or degradation of existing forests, i.e. make the use of wood sustainable and help avoiding GHG emissions to the atmosphere. Maintaining the balance between annual forest growth and annual fellings of wood is one of the major indicators of the sustainability concept [18]. When supplying energy from wood in Uganda, it is assumed that the concept of sustainability can be translated as *renewability* of the energy source.

As a first step, data on wood demand are compared to the biomass growth of natural resources to assess the fraction of non-renewable biomass extracted in the study area. We define the non-renewable biomass fraction, $FRAC_{NRB}$ as the fraction of wood removals exceeding the vegetation growth on total removals:

$$FRAC_{NRB} = \frac{(BD - G)}{BD} \quad (2)$$

where BD: biomass demand in a certain area (t y^{-1}), G: biomass growth in the same area (t y^{-1}).

Second, the emissions caused by the non-renewable biomass extracted annually are calculated by converting the non-renewable biomass to CO_2 emissions. A wood carbon fraction of 0.47 is assumed. Therefore, each tonne of non-renewable biomass burnt releases 1.83 t of CO_2 in the atmosphere.

Third, the area of plantations needed to substitute the non-renewable biomass and to avoid the related emissions is calculated. The plantation area needed depends on the productivity, the amount of fuelwood that can be extracted from the total biomass and the rotation length of the plantation. The area is estimated by assuming that plantations are similar to the Eucalyptus SRCs previously described with an average productivity of 10 t ha^{-1} y^{-1} on an oven dry basis.

It is assumed that the total demand of wood in the region remains constant over time and that the renewable fraction of wood is still supplied by natural wood resources.

The non-renewable biomass fraction is assessed for the entire Gulu district and for the Anaka IDP camp by using the two following alternative methods.

The Amuru district was still part of the Gulu district before 2006 and the available statistics refer to the old administrative borders. Therefore, the assessment of the $FRAC_{NRB}$ is done for Gulu and it includes the area of Amuru. The non-renewable biomass fraction in the Gulu district is assessed by using national removal statistics by FAO, representing the demand, and biomass growth data from the National Biomass Study (NBS) of Uganda [8].

Since data on wood removals are not available at the regional level, the national statistics are regionalized to assess the amount of wood demand in Gulu. The fuelwood demand is strongly related to the population residing in a certain area. Therefore, the proportion of the national amount of fuelwood extracted in Gulu is calculated by using the percentage of the population in the district (2%). The industrial roundwood extraction in Gulu, instead, is assessed by calculating the proportion of forest biomass in the district of the total forest biomass in Uganda and by assuming that the percentage of industrial roundwood removed would be the same. The wood removals are converted to total biomass with IPCC default factors [11].

The biomass growth is calculated based on information from the NBS of Uganda (Table 2). The total annual growth is equal to the aboveground annual increment converted to total biomass. Also in this case, we used IPCC default factors.

Alternatively, the $FRAC_{NRB}$ is assessed also for the area around the Anaka IDP camp by using a second method. In this area, the fuelwood demand is calculated based on a wood consumption of 601–692 kg of fuelwood per capita [19,20] and the Anaka population of 22,450 people. Based on these data, it is calculated that the total fuelwood demand in Anaka is 13,500 to 15,500 t y^{-1}. The fuelwood demand is converted to biomass affected by harvesting with IPCC conversion factors.

A land use map of the study area and the National Biomass Study (NBS) data on the biomass growth are used to estimate the biomass resources available to the IDP camp. Fuelwood is collected within a certain walking distance usually of 1 km, but people can cover a 20 km distance if needed. Three different areas with radii from the IDP camp of 5 km, 10 km and 15 km respectively are selected to calculate the available amount of wood within variable distances and $FRAC_{NRB}$ (Fig. 2). It is assumed that all the wood collected or purchased is available within these distances.

3. Results

3.1. *Biomass for electricity generation*

The GHG Balance shows that the wood gasification system produces less GHG emissions than the reference fossil fuel system of diesel generators (Fig. 3). When the plantation productivity is low (5 t ha^{-1} y^{-1}), the gasification system produces about half of the GHG emissions produced by the fossil fuel system (51%). The emissions are even lower if SRCs have higher productivity, i.e. if the average carbon stock of the SRCs is higher. When the plantation produces 15 t ha^{-1} y^{-1} of wood, the installation of a gasifier produces about 1/3 of the emissions produced by diesel generators. Therefore, the gasification system saves 18.1–24.6 t y^{-1} or 0.61–0.83 t MWh^{-1} of CO_2-eq. emissions.

The overall GHG balance of the gasification system is given by different components (Fig. 4). Emissions are produced by the management of SRCs (harvesting, fertilization, transport of workers and seeds), the transport of wood, the gasifier (construction material, diesel for the operation of the system), and the construction and operation of the electricity grid. These emissions are partially offset by carbon sequestration due to conversion from grasslands to Eucalyptus plantations (Land Use Change). The extent to which emissions are offset depends on the productivity of the plantations.

3.2. *Biomass for traditional use*

The National Biomass Study (NBS) clearly shows that the biomass stock of natural wood resources is decreasing all over Uganda. The trend is mainly caused by the gap between the high demand for fuelwood and the biomass increment [8].

By regionalising the national statistics, it is assessed that 722,000 m^3 of fuelwood and 19,100 m^3 of roundwood were removed in Gulu in 2005. By converting these figures to total biomass, it is estimated that 4.84 Mt y^{-1} of biomass was harvested or 3.23 Mt y^{-1} when only aboveground biomass is considered. From the supply side, we calculate that the total annual biomass growth in Gulu is equal to 3.82 Mt y^{-1} (2.55 Mt y^{-1} aboveground growth).

Based on these numbers, the non-renewable fraction of biomass extracted in Gulu ($FRAC_{NRB}$) is 21.1%.

Similar results are produced for the Anaka IDP camp with the alternative approach described in the Methods.

The difference between biomass demand in Anaka and biomass produced on land around the camp shows that the net biomass balance is negative within a distance of 10 km radius from the IDP camp. If the biomass would be extracted homogenously in the 15 km radius area, the fuelwood extracted would be all renewable, but within a 15 km radius there is higher competition of use with other settlements (Fig. 2). The percentage of non-renewable biomass that is extracted ranges between 88 and 89% in the 5 km radius to 18–29% in the 10 km radius (Table 3).

The non-renewable biomass extracted for fuelwood around the Anaka camp produces an annual amount of CO_2 emissions equal to:

- 151.5–177.6 × 10^3 t y^{-1} if fuelwood is collected within 5 km; or 7.3 t y^{-1} per capita on average.
- 31.6–57.8 × 10^3 t y^{-1} if fuelwood is collected within 10 km; or 2.0 t y^{-1} per capita on average.
- zero CO_2 emissions if fuelwood is collected within 15 km.

These results do not take into account that biomass is declining and that the percentage of non-renewable biomass increases with time.

In the Gulu district, the calculated 21% of non-renewable biomass releases each year 1.76 Mt of CO_2 emissions in the atmosphere. These emissions could be avoided by promoting the establishment of dedicated plantations or tree farming (e.g. trees around fields) that would substitute the use of non-renewable biomass.

By assuming a productivity of 10 t ha^{-1} y^{-1}, and a per capita fuelwood demand of 647 kg y^{-1}, the required plantation area is 1283 ha within a 5 km radius for a $FRAC_{NRB}$ of 88%, while only 348 ha would be required within a 10 km radius for a $FRAC_{NRB}$ of 24%.

The use of wood in the area would change from unsustainable use to sustainable use due to the additional wood supply from these plantations.

Based on the results from the GHG Balance for the wood gasifier, it can be conservatively assumed that the balance

Table 2 – Data on vegetation types in the Gulu District. The data refer only to the aboveground biomass (source: NBS).

Vegetation	Area	Biomass		Biomass change		Biomass increment	
	km^2	kt	t ha^{-1}	kt y^{-1}	%	t ha^{-1} y^{-1}	kt y^{-1}
Forest	8	99	131.0	−0.2	−0.2	13.0	9.8
Woodland	4686	14363	30.6	−737.5	−5.1	5.0	2343.1
Bushland	359	420	11.7	−13.6	−3.2	1.0	35.9
Grasslands	1624	1801	11.1	−3.4	−0.2	1.0	162.4
Total	6677	16683	25.0	−754.6	−4.5	n.a.	2551.2

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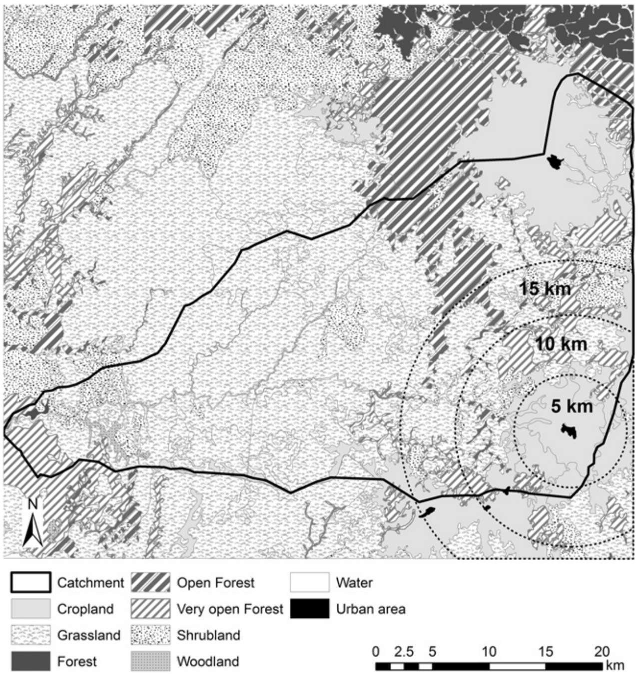

Fig. 2 – Land use map of the water catchment in which the Anaka camp is located [8]. The dotted circles around the camp define the wood supply areas within variable distances.

between carbon sequestration and emissions due to installation and management of the plantations is zero.

3.3. *Efficiency in producing emissions savings*

The previous sections showed that fast growing plantations could help achieving GHG emission reductions in rural Uganda either if the wood is used to produce electricity or as fuelwood. The efficiency of these two activities in producing emission savings can be compared by calculating the emission reductions achievable on a per hectare basis.

3.3.1. *Gasification system*

The gasification system saves on average 21.3 t y^{-1} of CO_2-eq. (18.1–24.6 t y^{-1}) compared to diesel generators by planting a total area of 3 ha of SRCs. Therefore the emissions saved by the gasifier are equal to 7.1 t y^{-1} per hectare of SRCs.

3.3.2. *Fuelwood production*

A fuelwood demand of 14,515 t y^{-1} annually required for the Anaka IDP camp produces 44,680 t y^{-1} of CO_2 emissions if the fuelwood is converted to total biomass extracted within a distance of 10 km radius from the camp ($FRAC_{NRB} = 24\%$). The total area of SRCs needed to offset these emissions is equal to 348 ha, meaning that the plantations for fuelwood save 128.2 t ha^{-1} y^{-1} of CO_2 emissions. The same result in terms of GHG saving per hectare is obtained when fuelwood is extracted within an area of 5 km radius from the camp.

Therefore, in terms of GHG savings on a per hectare basis, the most efficient use of fast growing plantations in rural Uganda is to replace fuelwood collected in forests managed unsustainably. However, the services provided by the gasification system and the fuelwood plantations are very different. Even if replacement of fuelwood is much more efficient from the point of view of GHG savings per hectare, the electricity services provided by the gasification system bring additional benefits (e.g. social development) that might render the use of plantations for electricity production more beneficial from a socio-economic point of view. The great difference of GHG savings might also depend on the IPCC factors that convert fuelwood to total biomass. According to these factors and the calculations made, the collection of fuelwood from natural wood resources is very inefficient, i.e. the amount of biomass affected by harvesting is 3.2–8.1 times higher than the amount used for fuelwood (the highest factor of 8.1 is for woodlands). In fact, only certain parts of the trees are

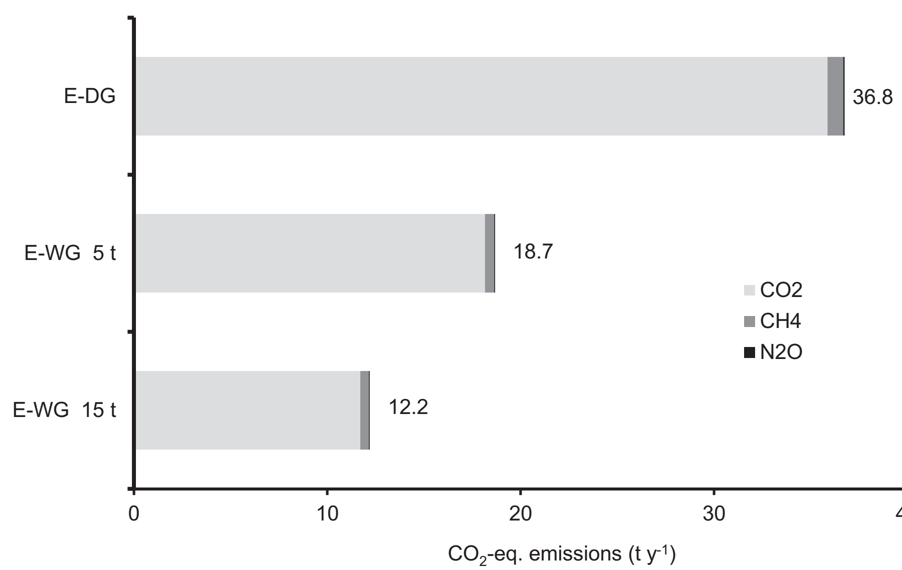

Fig. 3 – Comparison of GHG emissions from the diesel generators (E-DG) and the wood gasifier (E-WG). The emissions from the gasifier are shown for different levels of productivity of the plantations (5 and 15 t ha^{-1} y^{-1}).

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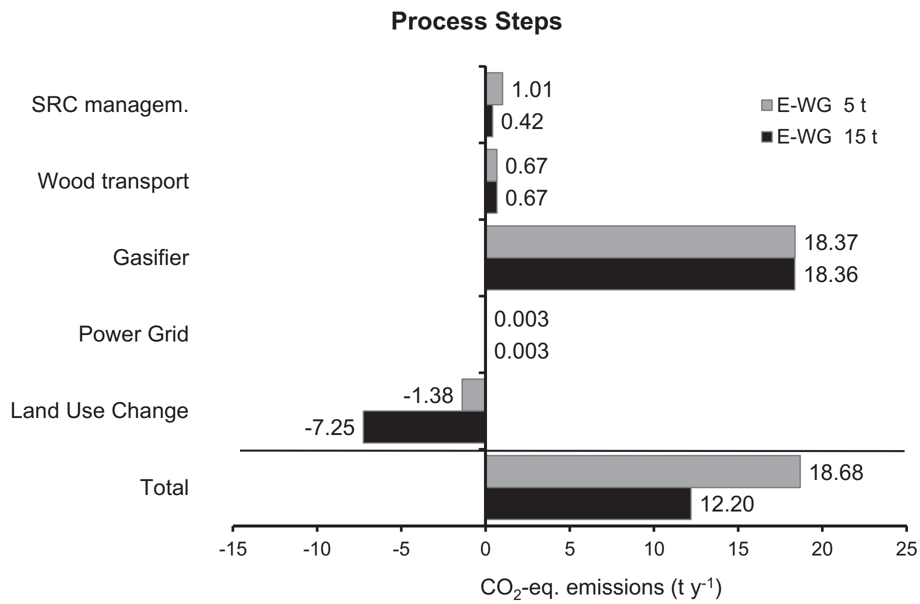

Fig. 4 – Emission components of the gasification system (E– WG) according to different productivities of the Short Rotation Coppices (SRCs).

collected for fuelwood, but the remaining biomass of the harvested tree remains in the field and starts to decay. Under a more efficient use, when most of the aboveground biomass from natural wood resources is used for fuelwood (about 70%) the CO_2 savings would be around 50 t ha^{-1} y^{-1}.

4. Discussion

According to the results in this study, wood gasification for electricity production could provide a valid alternative in terms of GHG impacts to diesel generation in rural communities in Uganda. The overall carbon balance shows that wood gasification could provide energy in rural communities that produces at least 50% less GHG emissions than the traditional diesel generators. The GHG balance improves if the productivity of the plantations increases.

The productivity of plantations is dependent on the tolerance of the tree species to local climate conditions and to the mortality rate due to fires and pests. In Amuru a short-term trial study showed that the productivity of Eucalyptus in the area could be very low and that a high mortality rate can occur because of fire, low peaks of rainfall and pests [7]. However, more detailed information would be needed to state that Eucalyptus is unsuitable in the study area. Alternative species to *E. grandis* more adapted to the Amuru area or hybrid Eucalyptus clones that are more resistant to dry conditions, such as *E. grandis* x *E. camaldulensis*, could be used. In addition, a different management, such as a different rotation length and tree density, could strongly influence the productivity of the SRCs.

Another parameter that should be considered to choose suitable tree species is its water use. It is recognized that Eucalyptus is a species that can produce high evapotranspiration. If planted on large scale areas, Eucalyptus could have negative impacts on the water balance in the catchment and limit water availability [21]. This problem should be addressed especially in zones, such as major parts of Africa, where scarcity of water for human consumption is an important issue.

We investigated the possibility to plant a native species such as *Markhamia lutea*, but data on its productivity were not robust enough to be used in the study. The use of native species could have the advantage to be more resistant to local conditions and therefore guarantee a more constant and secure wood supply. In addition negative effects on biodiversity and water balance could be avoided.

Table 3 – Fraction of non-renewable biomass removed within a certain distance from the Anaka IDP camp. The ranging values are determined by different fuelwood demands per capita.

	15 km	10 km	5 km
Fuelwood demand (kt y^{-1})		13.5–15.5	
Tot biomass demand (kt y^{-1})		100.4–115.6	
Biomass growth (kt y^{-1})	198.5	82.1	12.5
Net biomass balance (1000 t y^{-1})			
Low	98.0	−18.3	−87.9
High	82.9	−33.5	−103.1
$FRAC_{NRB}$ (%)			
Low	0	18	88
High	0	29	89

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Major limits to the presented results emerge from the uncertainty of the input data. As illustrated in the previous paragraphs, more precise information on the productivity of the plantations could narrow down the variability of the final results. Emissions or removals in the soil pool from land conversion should also be included, whereas they were neglected in this study due to the lack of more specific data for similar regions. In addition, large part of the input data to the model GEMIS were not specific for Uganda. A further limit of the study is that we focused only on the GHG impact of the gasification system. A complete environmental impact assessment, including more impact categories, would improve the understanding of the sustainability of such systems. Factors that affect the feasibility of implementation of gasification systems in rural areas should also be taken into account. Barriers to technical implantation could be: mechanical and technical problems when running the gasification system, unavailability of dried and chipped wood and social problems [22]. Moreover, public and private investments that provide the initial capital to establish the gasification system and the plantations should be identified to evaluate the feasibility of such installations (e.g. soft loans, microcredits, Clean Development Mechanism projects) [23].

This study encourages further investigations of social, economic and technical viability of such small-scale biomass gasification systems for rural electricity production in Uganda. Small-scale biomass gasification systems providing basic electricity services can have many economic and social advantages towards other renewable and non-renewable electricity sources and often constitute the only current economic alternative to diesel generators in rural Uganda. As little as 68 kg of dry wood per capita and year can already provide significant increases in life standards for rural residents in Uganda when used for electricity generation thus keeping the additional environmental pressures low [9].

The study assessed that the present use of wood for fuel in Amuru district is most likely unsustainable. However, the background data are highly uncertain, in particular the data on removals and the conversion factors to assess the total biomass affected by fuelwood extraction. It is also likely that a significant share of the wood removals is not reported by official statistics. If this is the case, the gap between wood removals and forest growth would be higher. Consequently the non-renewable fraction of biomass would be higher than the one estimated in this study and a larger area of plantations would be needed. In addition, the study does not take into account that the non-renewable fraction of biomass will increase over time if natural wood resources will continue to shrink. On these grounds, the estimates of $FRAC_{NRB}$ should be considered conservative. On the other hand, conversion factors to assess the total biomass affected by fuelwood extraction might overestimate $FRAC_{NRB}$.

Since wood will still be the main source of energy in Uganda, at least in the short to medium term, solutions to decrease pressure on natural resources should be proposed, including the increase of wood resources through additional forest plantations. An alternative to plantations is the increase of energy use efficiency through, e.g., the use of improved wood stoves. However, it is reported that increased efficiency does not necessarily lead to a decrease of wood consumption [2]; this phenomenon is known as the Jevons paradox [24].

An additional problem linked to the use of woody biomass is indirect land use change. When plantations are established on land that would have been used for other purposes, it is possible that the other uses are displaced somewhere else. The displacement can produce land use changes elsewhere and consequent negative environmental impacts (e.g. GHG emissions, biodiversity loss). For this reason, we suggested to establish the plantations on areas extensively used or that are marginal (grasslands). However, re-distribution of land after the civil war could re-convert large areas to agricultural use and compete with the establishment of new plantations.

5. Conclusions

The establishment of new tree plantations for energy production could be beneficial for rural communities in Uganda for both GHG emission reductions and the sustainability of biomass supply.

The analysis of the GHG benefits of a small-scale gasification system showed that it would be a valid alternative in terms of GHG impact to the diesel generators for areas that will not have access to hydropower or other forms of electricity generation in the short to medium term due to their distance to established electricity grids, low population density, and biophysical and geographical features. Wood gasification could provide electricity for basic community services by planting less than 10 ha of new Short Rotation Coppices and it could save 50–67% of the CO_2-eq. emissions produced by traditional diesel based electricity generators (18.1–24.6 t y^{-1} or 0.61–0.83 t MWh^{-1}).

Wood plantations should also be considered to reduce pressure on natural resources due to traditional use of wood in households in Uganda. It was assessed that the fuelwood removals in a rural area in Uganda are unsustainable because the demand for wood exceeds the annual growth from existing forests and other wooded lands. This situation substantially contributes to the degradation of natural biomass resources and, as a consequence, to GHG emissions. The non-renewable fraction of biomass that is extracted (21% in the Gulu district) could be replaced with wood from new plantations to render the overall balance of fuelwood removals sustainable and reduce emissions to the atmosphere. It was assessed that 0.02–0.06 ha per capita of plantations in a rural community in Uganda could avoid the GHG emissions produced through unsustainable extraction of wood (approximately 2.0–7.3 t of CO_2 per capita per year).

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Appendix

Inventory table for the wood gasification systems.

	Unit	Eucalyptus 15 t	Eucalyptus 5 t
SRC cultivation and harvesting			
INPUT			
Auxiliary energy			
Diesel	MWh MWh^{-1}	0.0014	0.0029
Petrol	MWh MWh^{-1}	0.004	0.012
Auxiliary material			
Engine oil	kg MWh^{-1}	0.083	0.250
Phosphate	kg MWh^{-1}	0.05	0.15
Herbicides	kg MWh^{-1}	0.01	0.04
OUTPUT			
Eucalyptus			
Yield (fresh matter)	t ha^{-1} y^{-1}	154	51
Water content	%	41.5	41.5
Heating value	MWh t^{-1}	2.64	2.64
SRC Transport			
Vehicle type		Small truck	
Loading capacity	t	3.5	
Fuel consumption	dm^3 km^{-1}	0.165	
Distance	km	60	
Gasifier			
INPUT			
Eucalyptus	MWh MWh^{-1}	4.87	
Auxiliary energy			
Diesel	MWh MWh^{-1}	1.79	
Construction material			
Steel	t MW^{-1}	56	
Concrete	t MW^{-1}	22	
OUTPUT			
Electricity			
Power grid			
Transmission losses	% km^{-1}	0.04	
Construction material			
Steel	t km^{-1}	550	
Concrete	t km^{-1}	45	

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